Magnetized Target Fusion

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Introduction

A new project called Magnetized Target Fusion (MTF), which involves Los Alamos National Laboratory (the Laboratory) in Los Alamos, New Mexico, and the Air Force Research Laboratory (AFRL) at Kirtland Air Force Base in Albuquerque, New Mexico, is aimed at a qualitatively different approach to fusion energy. Unlike conventional tokamak and laser fusion approaches, MTF has the potential of creating fusion energy in an inexpensive apparatus. In recent years the focus of effort for fusion researchers, especially in the United States, has shifted from scientific feasibility to economic practicality. If successful, the cost savings implied by the MTF approach would allow fusion to be developed on a much faster time scale than conventional fusion.[1,2]

The MTF approach to fusion preheats and injects fusion fuel into a volume the size of a beer can as shown in the figure. Then the “beer can” (AKA aluminum cylinder) is rapidly compressed by magnetic forces that ensue from drawing a giant electrical current pulse axially along the wall of the cylinder. The compressed, high-density plasma fuel then burns in a few microseconds. The fast moving metal wall, driven by pulsed-power liner technology, has been developed for other purposes by defense programs and is a specialty of New Mexico laboratories. The left side of Figure 1 shows the plasma injector, and the right side shows the liner compressor region, which implodes under millions of atmospheres of pressure. The process is analogous to that of a diesel engine, which compresses fuel to conditions where it burns more readily. The essential advantage of MTF is its potential to be tested for scientific feasibility and even developed to the stage of prototype power generation using an apparatus that costs orders of magnitude less than either conventional magnetic- or inertial-fusion approaches.

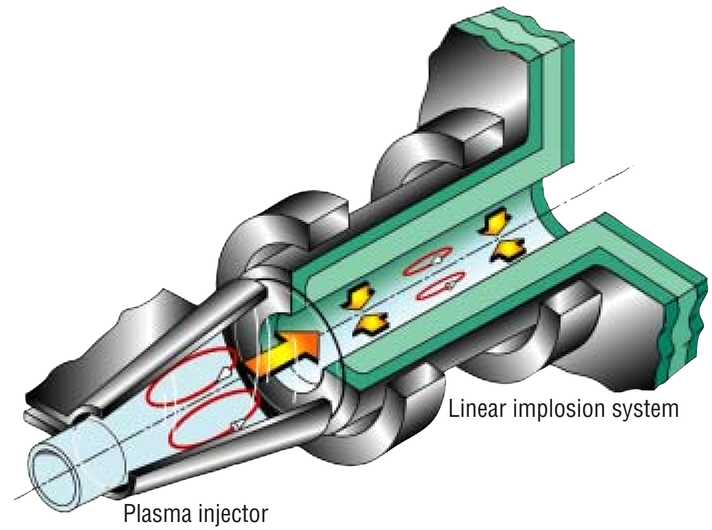

Figure 1. MTF will require us to create the initial plasma configuration, inject it axially into a flux-conserving shell, and finally compress the plasma to fusion-relevant density and temperature.

Context of MTF in Magnetic Fusion Energy Research

To explore this truly different fusion concept, we are taking advantage of the past 20 years of compact toroid (CT) research in the Magnetic Fusion Energy program (MFE). The CT plasma chosen for the target is a high-density field-reversed configuration (FRC)[3] similar to the early reversed-field theta pinch work carried out at the Naval Research Laboratory on PHAROS[4], at Julich on JULIETTA[5], and at Garching[6]. Similar to earlier work at the Laboratory, we will translate the FRC (see review paper)[7] into a compression region but then compress it using well-established liner technology developed in recent years by Department of Energy and Department of Defense program research. As sketched in Figure 2 there are "O" points that correspond to the nulls (B = 0) in magnetic field.

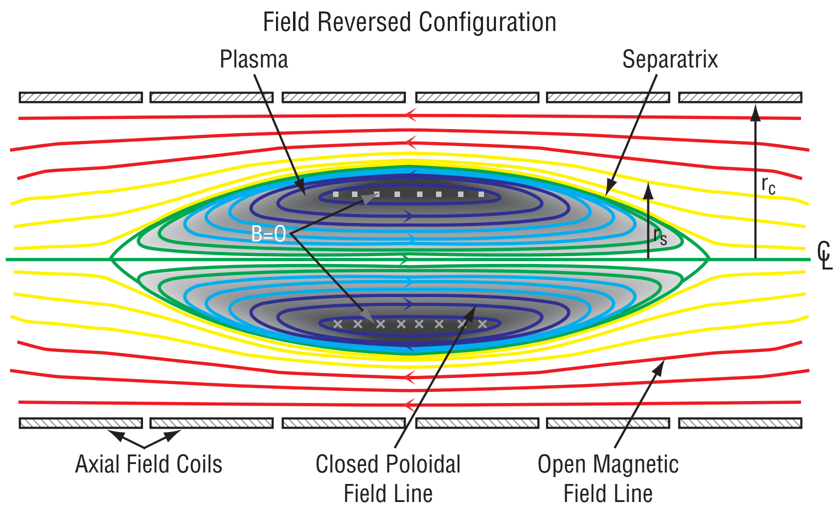

Figure 2. FRC equilibrium geometry, showing the closed magnetic surfaces that constitute a toroidally shaped magnetic equilibrium which is in force balance with the external magnetic field (red lines pointing to the left).

The crosses and dots also show the centroid of a doughnut or toroidally shaped circulating electrical current, which exits the figure on the top (dots) and re-enters the figure on the bottom (crosses). Surrounding the toroidal plasma current distribution are closed magnetic surfaces indicated by the arrows. These magnetic field lines circulate poloidally according to the right-hand rule, counter clockwise about the dots and clockwise about the crosses. Note that the field lines are reversed on the inside compared to the outside, which is why we name this plasma equilibrium a FRC. Charged particles have difficulty diffusing across the magnetic-field lines and surfaces. Hence these closed toroidal magnetic surfaces of the FRC should provide enough thermal-energy confinement during compression inside a metal liner flux conserver to allow compressional work and heating of the plasma to fusion-relevant conditions. There is also an "X" point at the left- and right-hand sides of the football shape where the external magnetic field points in the opposite direction to the internal magnetic field on axis. This also corresponds to a null in magnetic field and accounts for some of the particle and energy losses in a FRC. Fusion energy will be generated in a microsecond pulse during which pressure (plasma and magnetic) is magnetically and inertially confined by the imploding liner wall. At the Laboratory, magnetic fields of this magnitude (200 Tesla) have already been confined in an explosively compressed shell[8] that was designed to test some of the MTF assumptions. Small-size and high-density fusion by MFE standards could achieve significant performance ($nt_E > 10^{13}$ s-cm^{-3}, T~5 keV) in just a few years at modest cost using available pulsed-power facilities, including the SHIVA Star capacitor bank driver at the Air Force Research Laboratory at Kirtland Air Force Base.

The density regime and time scale of MTF is intermediate between MFE and inertial confinement fusion (ICF). Three technical considerations explain why the regime is important. First, fusion reactivity scales as density squared; MTF density can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence, system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the power and precision required to compressionally heat plasma to fusion-relevant conditions compared with ICF and brings the pulsed-power requirements within reach of existing facilities.[2]

Table 1 shows parameters of the FRC target plasma at the formation stage and the predicted final fusion relevant conditions for this FRC after compression by the MTF liner.

The initial density of 10^{17} cm^{-3} is large compared to present-day FRC experiments but consistent with experiments of thirty years ago[4,5,6] that we will describe in more detail in a later section on the history of FRC research. The initial temperature of 250 eV or approximately 3 million degrees Celsius must be large enough so that radiation from partially ionized impurity atoms (Bremsstrahlung) will not dominate the power balance. The formation 5-Tesla magnetic field is large and will provide us a large latitude in choosing the internal magnetic reversed "bias" magnetic field (in the vicinity of 10% of the 5-Tesla formation field). The field energy from the bias magnetic field is dissipated into particle energy that would be observed as a plasma temperature for whatever particle density we choose for the formation FRC. During compression of this plasma inside the MTF liner, work is done on the plasma and its energy, and magnetic field consequently increases to the parameters noted on the right-hand column of Table 1. It can be shown that the magnetic flux (product of axial magnetic field times the circular area) is conserved during this process. Because the area gets vanishingly small at the end of the compression, the magnetic field grows enormously. This 500-Tesla magnetic field confines the hot charged particles to small gyro orbit radii and thus magnetically insulates the hot plasma. The dwell time of the converging shell at maximum compression is a fraction of a microsecond and occurs when the inward implosion forces are balanced by the internal plasma pressure pushing radially outwards. We expect the lifetime of the FRC to be at least this long in this final compressed state.

Table 1. FRC target plasma pre- and post-compression parameters.

FRC Parameters	FRC Parameters at Formation	FRC Parameters after Flux Compression (100×)
Density	*0.5–1 × 10^{17} cm^{-3}*	*≈ 10^{19} cm^{-3}*
Temperature Te ≈ Ti	*250 eV*	*10 keV*
Magnetic Field	*5 Tesla*	*500 Tesla*
Lifetime	*15–20 μsec*	*200 nsec*

Any fusion-power reactor design that follows from this path is obviously pulsed, and pulsed concepts have fallen out of favor compared with steady-state reactor designs. "Low" density, "long" pulse tokamaks operate at densities of n ~10^{14} cm^{-3}, but the large 2–10-billion-dollar price tag for proof-of-ignition devices such as the International Thermonuclear Experimental Reactor (ITER) compels us to consider other options. Some people argue that we need a technology breakthrough for the MFE tokamak approach. Another very different possibility is ICF at very high density and pressure. The cost for this approach evidently exceeds $2 billion for the National Ignition Facility (NIF).

On the other hand, it may turn out that the engineering problems of pulsed-power-plant concepts are easier to solve than the steady-state ones.[2] We are engaging in a high-risk, high-payoff investigation of MTF as one of the concepts alternate to the tokamak fusion power-plant designs that presently dominate the MFE world view. MTF has intermediate density n_{MTF} ~10^{20} cm^{-3} which is approximately one million times the MFE tokamak scenario and approximately one million times less dense than the ICF paradigm $n_{MTF} \sim 10^{6}\, n_{MFE}, \approx 10^{-6}\, n_{ICF}$ at a temperature near 10 keV. This has the consequence that megabar pressures are accessible, at the price of an intrinsically pulsed scenario. The liner imparts energy via integrated $\int PdV$ work that heats fuel by compressing it inside an imploding "pusher" wall. A magnetic field embedded in the fuel thermally insulates it from the pusher.

Recent Experimental Results

In April 1999, a joint Laboratory/Air Force collaboration demonstrated MTF-relevant liner technology. We used the SHIVA-Star capacitor bank facility at the AFRL in Albuquerque to generate 11 Mega-Ampere current pulses into a cylindrical flux-conserving shell. These successful results gave credibility to a joint Laboratory/AFRL proposal to carry out proof-of-principle experiments creating a MTF-relevant FRC. Experimental results of this successful first step confirm a shell exceeding the requisite characteristics to compress a FRC suitable for MTF. These requirements include high compression ratio and symmetry for a 3:1 aspect ratio thin liner. X-ray photographs (see Figure 3) show excellent uniformity for three snapshots of the shell radius as it radially converges to the axis. The top radiograph was taken before the compression started and shows the outer shell at radius of 4.89 cm and the inner diagnostic stalk at a radius of 0.317 cm. The second radiograph shows the compression approximately half way converged.

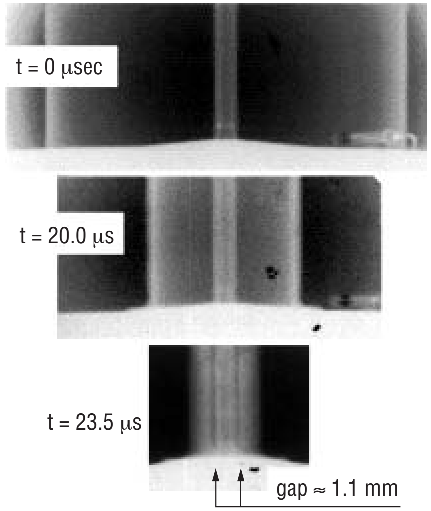

Figure 3. Side-on radiographs near the lower glide plane of initial liner and at three times t = 0.0, 20.0, and 23.5 μsec during the implosion. The 0.64-cm stationary probe jacket which contains magnetic and optical probes is visible on axis.

Note the final radiograph, which shows a very small gap between the central probe stalk with our various magnetic field diagnostics inside and the interior of the flux-conserving cylindrical shell. The bottom radiograph corresponds to a final compression ratio of 11.5:1 in radius, and compression to the probe stalk radius would correspond to a compression ratio of greater than 15:1.

We created a small magnetic field for this experiment that was trapped inside the converging flux conserver as the compression proceeded. Independent experimental measurements of the time-dependent internal magnetic field were extracted from magnetic coil detectors and optical Faraday rotation measurements of magnetic field. The axial magnetic flux was defined as the product of the axial magnetic field and the area inside the conducting boundary (the aluminum cylindrical shell in our case). It can be shown that the flux is conserved, so that a measurement of the internal magnetic field history is equivalent to measuring the time evolution of the interior cylinder radius and its speed. Time histories of these data are shown in Figure 4, where the singular behavior as the radius converges to zero is evident. These data are consistent with each other.

We take advantage of the flux-conservation argument to infer the radius r(t) as shown in Figure 5. Fiber-optic impact detectors (FIDs) were also embedded in the central probe stalk on axis. They show the symmetry and arrival time of the implosion. The radial symmetry appears to be better than 1% (*i.e.*, ±300 μm out of an initial liner radius of 4.89 cm). All of the data are displayed in Figure 5, where good agreement is evident between data from several Bz probe locations, the radius inferred from the radiographs, the FID impact data and a model invoking the actual capacitor bank circuit with no free parameters.

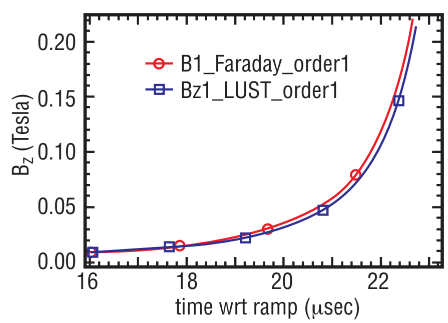

Figure 4. Faraday Bz data at the midplane compared with the adjacent Bdot probe data.

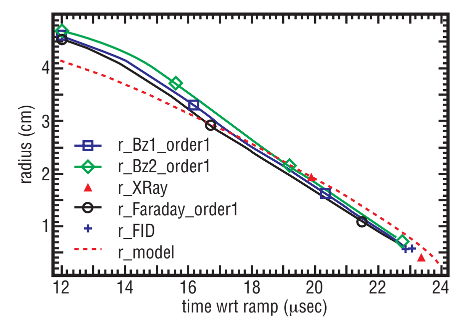

Figure 5. Time history of the inferred shell radius near the midplane. Data from Bdot, Faraday, FID, and radiographs are overlaid and quite consistent with each other.

Field Reversed Configuration Research has a Long History at the Laboratory

Our immediate goal for this year is to demonstrate, in the laboratory, a suitable FRC target plasma for MTF. The FRC is a type of "theta pinch" which consists of azimuthal image currents in the core plasma that are induced by opposite azimuthal currents in the exterior magnetic coil. A large magnetic field encircles this plasma image current to form toroidal- (doughnut) shaped closed magnetic field surfaces, as shown in Figure 2. It turns out the similar high-density FRC's were created in the early days of magnetic fusion research in the late 1960s. Scientists were not yet aware that such a reversed magnetic equilibrium could exist, but rather that such a reversed field "frozen" into the plasma increased the number of neutrons counted. The quest for fusion-relevant plasmas and increased neutron fluxes had the consequence that we know these MTF-relevant theta pinches were created, but not much detailed data was ever published. Over the next few decades, the typical FRC density decreased by a factor of 100 as researchers attempted to increase the lifetime of their plasma equilibria. The MTF concept is intrinsically pulsed and only requires a short equilibrium lifetime of 15–25 μsec for the target plasma we plan to inject into the compression region. This duration is well within reach of the published FRC theta pinch data.[4,5,6] Our experimental program takes advantage of many years of FRC research experience at the Laboratory. We will improve our understanding of high-density FRC's that were a hot topic 30 years ago, as we create them in the laboratory.

Field Reversed Configuration Target Plasma is Coming Online Soon

After somewhat more than one year of preparation, the first in a series of FRC experiments is coming on line at the Laboratory with considerable logistical help from the AFRL. The 15-person experimental team comprises fractions of 4 Technical Staff Member scientists from the Laboratory and AFRL, 5 technicians, and approximately 6 students. We have fabricated all the necessary hardware and are integrating the entire experiment. This requires several sets of capacitor banks, pulsed-power switching systems, safety interlocks, and suitable diagnostics of plasma properties. Figure 6 shows the pre-ionization capacitor bank on the bottom and the COLT theta pinch 0.25-megajoule capacitor bank on the left.

We expect the first plasma in mid-February 2001 for an experiment to explore strategies that could pre-ionize the plasma. The high-density FRC theta pinch experiment is expected to be operational in late June 2001. Plasma chararcteriz-ation will be our focus in FY02. We plan to perform the first integrated FRC plasma/liner implosion experiments at the AFRL in Albuquerque beginning in FY03. The near-term goals for FRC MTF Project are

1. to have a working FRC experiment in the laboratory, with safety documentation, pre-ionization, bias, theta pinch, and cusp banks operational (no translation);
2. to have a full complement of diagnostics on the FRC in the quartz tube (this includes measurements of density, temperature, magnetic fields, and impurities); and
3. to explore the operating space for finding an optimum FRC target plasma (including how it behaves when translated into a "fake" aluminum liner).

The question is: just how close to an ~10^{17} cm^{-3}, 100–300 eV, 15–25 μsec lifetime FRC plasma do we come?

Figure 6. Standing in front of the FRX-L main capacitor bank and behind the main header current feed assembly, are (from left to right, all Laboratory personnel unless otherwise indicated) Glen Wurden, Bill Waganaar, Daniel Begay, Matt Langner, Kit Werley, Ed Mignardot, Bill Fienup, Kathy Barela, Chris Grabowski (AFRL), Tom Intrator (Principal Investigator), Ricky Maqueda, Philip Sanchez, Bernie Martinez (AFRL).

Conclusion

MTF is beginning to be recognized as a dark-horse candidate approach to fusion energy. The MTF vision is easy to recognize, and we believe it is one of the few things in today's fusion program that actually produces excitement (.... that it just might work and is so cheap, that we ought to just go "do it").

MTF has goals which are simple to explain to both the general public as well as potential postdocs and staff. There is some relation to pulsed power technologies originally developed for defense programs at the Laboratory. This is why we can leverage our local Laboratory expertise and hardware into an extremely cost-effective experiment. However, all of our work is in the open literature.

For the actual embodiment of the MTF concept into a fusion power reactor, one needs to solve the engineering challenges of an intrinsically pulsed reactor scenario. A steady-state scheme is preferred by most power-company engineers. But as we noted already, it may turn out that the engineering problems of pulsed fusion power-plant concepts are easier to solve than the steady-state ones.[2] We are engaging in a high-risk, high-payoff investigation of MTF as one of the concepts alternate to the tokamak-fusion power-plant designs that presently dominate the MFE worldview. Interestingly, the most common reaction when we present MTF is not that it can't work or is on too unrealistic of a time-schedule, "but how can it be a reactor?"

The MTF high-density FRC experiment is the first step in a long-range program that could have a smaller budget and shorter time scale than the mainstream fusion energy options. The energy crisis is real and present, and current events such as global warming and electrical energy deregulation in California only serve to underscore this point. We feel that in the long run, our children will need to pay a high price if we do not address alternative basic energy-producing technologies today. Many of us still harbor the idealistic dream of producing and studying a viable fusion-energy source before we retire.

Contact Information

For further information, contact the Los Alamos Fusion Energy Program Manager, Richard E. Siemon, or visit the fusion energy web page: http://fusionenergy.lanl.gov.

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